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Cr_2O_3 as a Foaming Agent in CaO-SiO_2 Slags +

Ph. D. J. H. Swisher

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J. H. Swisher and C. L. McCabe
Carnegie Institute of Technology

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ABSTRACT

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An experimental study has been made of the possible mechanisms for foam stability in the system $\text{CaO-SiO}_2\text{-Cr}_2\text{O}_3$, where Cr_2O_3 is the foaming agent. The degree of lowering of surface tension by Cr_2O_3 was determined at 1600°C for high-silica melts. Measurements were also made of foam stability under standardized conditions. The results of the two sets of measurements then were correlated by applying the Gibbs' and Marangoni theories of film elasticity. It was demonstrated that the Marangoni elasticity effect is probably the largest single contributor to foam stability, although the high viscosity of silicate melts makes some contribution in controlling the rate of drainage of liquid from bubble lamellae.

AUTHOR

* Formerly a Student Member, AIME, is now a First Lieutenant, U. S. Army, assigned to the NASA - Lewis Research Center.

**Member, AIME, is Professor and Head, Department of Metallurgical Engineering, Carnegie Institute of Technology.

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The tendency of metallurgical slags to foam has frequently been observed during steel refining operations. In the open-hearth furnace, this tendency is considered undesirable. It slows down the rate of heat transfer from the burners to the molten metal bath, making automatic control of the burners impossible. On the other hand, it is sometimes desirable to have a "foamy" slag in the basic oxygen converter.⁽¹⁾ A flush slag can be removed more easily in this condition. Even when using a single slag process, a more effective blanket over the steel bath is made by a "foamy" slag, and loss in yield of metal due to splashing is minimized.

Since slag foaming problems in the field have been attacked largely on an empirical basis, it appeared desirable to obtain a better basic understanding of the mechanism of foam stability. The experimental work was directed almost entirely toward the behavior of Cr_2O_3 as the foaming agent in $\text{CaO-SiO}_2\text{-Cr}_2\text{O}_3$ melts. In the first stage of the investigation, the degree of lowering of surface tension by Cr_2O_3 was determined at 1600°C . In addition, measurements were made of foam stabilities under standardized conditions; then the two sets of experimental results were correlated by applying various theories of foam stability. For convenience in interpreting the surface tension and foam stability results reported here, a portion of the $\text{CaO-SiO}_2\text{-Cr}_2\text{O}_3$ phase diagram⁽²⁾ is reproduced in Figure 1.

EXPERIMENTAL

1. Surface Tension Measurements

Very little information is available in the literature on the lowering of surface tensions of slags by foaming agents. Kozakevitch⁽³⁾ mentioned that

the addition of 1.5 percent Cr_2O_3 lowered the surface tension of FeO slightly. In another system, some data on the lowering of surface tension of foaming slags by P_2O_5 were reported by Cooper and Kitchener.⁽⁴⁾

The technique used for the surface tension measurements was the maximum bubble pressure method,⁽⁵⁾ using a single tube immersed to various depths in the melt. This method has been used extensively in high temperature systems such as in liquid metals, slags, and glasses.^(6,7) It has the advantage that the contact angle between the liquid and the tube material need not be known.

The equation used for calculating surface tension values from maximum bubble pressure measurements is the Schroedinger equation⁽⁵⁾, which can be written as follows:

$$\gamma = \frac{rg}{2} \left[h\rho_{mf} - z\rho_x \right] \left[1 - \frac{2}{3} \frac{r\rho_x}{A} - \frac{1}{6} \left(\frac{r\rho_x}{A} \right)^2 \right],$$

where γ is the surface tension of the melt, r is the orifice radius of the tube, g is the gravitational constant, h is the manometric height associated with the maximum pressure obtained during the growth of a bubble, ρ_{mf} is the density of the manometer fluid, z is the depth of immersion, ρ_x is the density of the melt, and A refers to the quantity,

$$\left[h\rho_{mf} - z\rho_x \right].$$

Analysis of the Schroedinger equation leads to the conclusion that the density of the melt, ρ_x , as well as its surface tension, are variables. By measuring h as a function of z , in principle γ and ρ_x can be determined simultaneously. No density determinations are reported here because the tendency toward foaming made them highly erratic and unreliable. The surface tension values were calculated from the zero depth intercepts of linear plots of h versus z .

A schematic drawing of the apparatus is shown in Figure 2. The molybdenum furnace windings were protected with a mixture of 5 percent H_2 and 95 percent argon, which was passed through the Al_2O_3 insulating powder. A vertical cathetometer was used to measure both the pressure maxima on the manometer and the depth of the tip of the bubbling tube in the melt. The latter was accomplished by sighting on a mark scribed on the upper part of the bubbling tube. Thin-walled tubing was used in the bubbling tube to eliminate variations in bubble size due to wetting effects. Dibutyl phthalate was used in the manometer because of its low vapor pressure and known thermal expansion characteristics. A more detailed description of the apparatus is given in reference 8.

At the beginning of each experiment, the surface of the melt was located by lowering the tube until a rise in the manometer was observed, indicating the formation of a bubble in the melt. About twenty maximum pressure readings then were taken at each of several depths of immersion. Median values for each depth were calculated, and the h versus z data were found to obey a linear relation. The fact that this relation should be linear was proven by implicit differentiation of the Schroedinger equation. A least squares analysis then was applied to the data to determine the value of the intercept, which was used for the surface tension calculation.

It was found necessary to keep the rate of bubble formation slower than one bubble every twenty seconds. Otherwise a larger "dynamic" surface tension was obtained as a consequence of insufficient aging times at the bubble surfaces. Viscosity also plays a role with high bubble rates. The actual pressure at the break-away point may exceed the pressure theoretically required due to viscous drag in the melt and give erroneous results.

The experimental results are given in Table I and in Figure 3.

Surface tension values were determined for each of three lime-silica molar ratios at 1600°C. Preliminary results on the CaO-SiO_2 binary system were found to compare favorably with those of other investigators. Popel and Esin⁽⁹⁾ and Copper and Kitchener⁽⁴⁾ gave results that were about 8 percent and 3 percent higher than the present results, while King's results⁽¹⁰⁾ were about 9 percent lower. Reproducibility of the results was established by conducting six experiments on melts of the same composition. The standard deviation in the surface tension values was found to be 1.9 dynes/cm.

Figure 3 illustrates that the addition of Cr_2O_3 yields an appreciable lowering of surface tension in the dilute solution range, which will be used later in explaining foaming tendencies. With the addition of more Cr_2O_3 , anomalous arrests were observed in the surface tension-concentration curves, which cannot be rationalized in terms of the variation of surface tension across a single, one-phase region. Instead, it was found that the surface tension arrests correspond to the phase boundary in Figure 1 which surrounds the two-liquid miscibility gap.

Therefore compositions exceeding the solubility limit of Cr_2O_3 lie in a two-liquid phase region. Ordinarily one would expect the two liquids to separate into distinct layers due to density considerations. In such cases, the measured surface tensions should have remained at their saturation values, provided that measurements were being made only in the upper layer, which was lean in Cr_2O_3 . The expected behavior was not observed, except for the 4.0 percent Cr_2O_3 composition with $\text{CaO/SiO}_2 = 0.77$. For the other two-phase melts, an apparent secondary lowering of surface tension

was observed. This effect can be explained in terms of an emulsification of the second liquid phase. During the course of the formation of a bubble in the melt, heterogeneous films containing both liquid phases could have formed at the bubble surfaces.^(11, 12) When this happens, the resistance to bubble growth is not simply the surface tension of a single saturated solution. The interfacial tension between liquids decreases the resistance to bubble growth and hence leads to an apparent secondary lowering of surface tension of the melt. This effect, then, was only important in that it showed that emulsification had occurred. Direct evidence for emulsification was obtained from microscopic observation of quenched slag samples.

Surface tension data similar to that appearing in Figure 3 were determined by King⁽¹³⁾ in silicate systems containing P_2O_5 and V_2O_5 . These results along with other results for Na_2O are reproduced in Figure 4. Based on the results for the Cr_2O_3 system, it is likely that miscibility gaps also exist in the P_2O_5 and V_2O_5 systems. It is interesting to note that while P_2O_5 , V_2O_5 , and Na_2O all lower surface tension, only P_2O_5 and V_2O_5 are foam stabilizers. Therefore a correlation seems to exist between systems that exhibit miscibility gaps and systems that are prone to foaming.

2. Foam Stability Measurements

A considerable amount of experimental work has been done on the subject of foaming in the field of colloid chemistry. There have been very few investigations, however, where controlled experiments have been performed on the foaming of glasses and metallurgical slags. Cooper and Kitchener⁽⁴⁾ made an extensive study of the foaming agent, P_2O_5 , in $CaO-SiO_2$ slags. Cooper and McCabe⁽¹⁵⁾ later showed that Cr_2O_3 and Fe_2O_3

are also foam stabilizers, but that FeO , MnO , Al_2O_3 , and the network-breaking basic oxides (Na_2O , MgO , SrO) are not important in promoting foaming.

The technique used for the foam stability measurements was identical to that used by Cooper and Kitchener.⁽⁴⁾ Columns of foam were produced by gas injection, and their rates of decay were measured under arbitrarily standardized conditions. This method was used in preference to single film studies because of the high temperatures involved in the experiments.

The apparatus and method are illustrated schematically in Figure 5. The furnace was the same as that used for the surface tension measurements (see Figure 2). The slags again were contained in platinum crucibles. A platinum wire harness containing foam level pointers was hung from the top of the crucible. The lower pointer was positioned about one-fourth inch above the surface of the melt, and the distance from the lower to the upper pointer was one and five-eighths inches. The composite frothing tube consisted of a Pt-10 percent Rh section at the lower end, which was soldered to a water-cooled copper section at the top. The lower part of the tube was about 0.1 in. outside diameter and 0.031 in. inside diameter, except at the tip, where the inside diameter was reduced to a fine capillary by hot working. The latter was done by trial; the objective was making an opening that could be used to produce 5 mm diameter bubbles in the slags using a pressure of about 5 psi. Great care was exercised in maintaining a constant bubble size because foams consisting of smaller bubbles are more stable, and it was desired to eliminate bubble size as a variable.

A sample of 20 to 25 grams of slag was melted from blended powders prior to each experiment. A column of foam was then built up until it reached

the upper pointer level. The time for the foam to decay to the lower pointer was measured with a stopwatch by observing the collapse of the foam through the viewing prism. A series of about twenty trials was conducted and the median value taken for each experimental point.

Extreme values differed from the median by about ± 20 percent. The primary variables studied were temperature and composition. Oxygen at one atmosphere pressure was used throughout for producing the foam columns. It should be emphasized that the results depend to a large degree on the geometry of the apparatus and other variables. Therefore, foam stabilities so defined can be compared only to others measured under exactly the same conditions.

The formation of dispersed platinum proved to be a rather serious complicating factor until it was eventually brought under control. In a previous investigation in which platinum crucibles were used, Cooper⁽¹⁵⁾ found that the foam stability of slags containing Cr_2O_3 increased as a function of time. The same behavior was observed in the early stages of the present investigation. Platinum particles about 10 microns in diameter were observed in the samples after solidification through microscopic examination, and when present in large amounts they increased foam life markedly.

Platinum is believed to be slightly soluble in oxide melts.⁽¹⁶⁾ It is thought in this investigation that platinum entered the melt by either a cyclic solution-precipitation process, an evaporation-condensation process, or a combination of both. The problem of the formation of dispersed platinum particles was overcome by eliminating temperature fluctuations associated with the automatic temperature controller and by completing measurements within a few hours after fusing. When these precautions were taken, consistent

results were obtained, and the melts were found to contain only small amounts of platinum. The experimental results are presented in Table II and in Figs. 6 and 7.

DISCUSSION

In Fig. 6, foam life can be seen to be greater for the more acid slags and for lower temperatures. The general shape of the curves is similar in appearance to viscosity-temperature data for silicate melts, which suggests that the high viscosity of slags is an important factor in producing stable foams. The fact that both foam life and viscosity increase with slag acidity also supports this hypothesis.

Other evidence, however, indicates that a direct correlation between foam stability and viscosity cannot be made. The data shown in Fig. 6 were used to calculate apparent activation energies for foam decay. The values obtained were in the neighborhood of 100 Kcal/mole, which is considerably higher than activation energies for viscous flow in silicate melts (about 40 Kcal/mole).⁽¹⁷⁾ Further evidence that viscous flow is not controlling is that the apparent activation energy for foam decay increased with increasing silica content, while the opposite dependence has been found for viscous flow. Other evidence that illustrates the limited importance of viscosity is that highly viscous CaO-SiO_2 binary melts will only support a stable foam when a surface active agent such as P_2O_5 or Cr_2O_3 has been added. It can therefore be concluded that viscosity considerations do not provide a complete explanation for foaming tendencies in slags.

As mentioned earlier, surface tension effects are major considerations in foaming studies. Although surface tension forces oppose the

expansion of the gas-liquid interface when a foam is produced, the magnitude of the surface tension of a foaming solution is of minor importance. The lowering of surface tension by foaming agents, however, has been found to be very important in producing a stable foam.

This phenomenon and its relation to foaming has been treated by Gibbs, Marangoni, and others. Gibbs⁽¹⁸⁾ proved thermodynamically that, at equilibrium, surface tension lowering must be accomplished by adsorption. The relation has been expressed quantitatively in the Gibbs' adsorption equation:

$$\Gamma_i = - \frac{1}{RT} \frac{\partial \gamma}{\partial \ln a_i},$$

where Γ_i is the surface excess concentration and a_i is the thermodynamic activity of component i . For the case of Cr_2O_3 in dilute solution in CaO-SiO_2 melts, Henry's law can be invoked in the absence of activity data to reduce the Gibbs' equation to a useable form:

$$\Gamma_{\text{Cr}_2\text{O}_3} = - \frac{1}{RT} \frac{\partial \gamma}{\partial \ln N_{\text{Cr}_2\text{O}_3}}.$$

In this equation, $N_{\text{Cr}_2\text{O}_3}$, the mole fraction of Cr_2O_3 , is substituted for its activity. Calculations based on the surface tension data shown in Figure 3 resulted in values of $\Gamma_{\text{Cr}_2\text{O}_3}$ varying from 2.5×10^{-11} moles/cm² for $\text{CaO/SiO}_2 = 0.77$ to 4.6×10^{-11} moles/cm² for $\text{CaO/SiO}_2 = 0.57$, when $N_{\text{Cr}_2\text{O}_3} = 0.002$. It is interesting to compare these values with a typical value for detergents in aqueous solutions (10^{-9} moles/cm²). The surface activity of a detergent can be seen to be significantly greater, which suggests that initial surface tension lowering may not be as important in explaining foaming tendencies in slags as it is in detergent solutions.

Gibbs also demonstrated that the isotherm can be used to describe an elasticity mechanism whereby thin films containing surface active agents resist mechanical deformation. Such a film has two interfacial layers containing adsorbed solute, separated by a layer of the bulk phase. As the film is stretched and its area increased, the total amount of solute at the interface must increase in order to maintain the surface excess concentration given by the adsorption equation. This can be accomplished only by removing solute from the bulk liquid. The diminished bulk concentration results in an increase in surface tension in the stretched area, in compliance with the surface tension-concentration dependence. The increased surface tension acts as a restoring force, which opposes further stretching and eventual rupture of the film. Thus the Gibbs' effect provides a potential mechanism of foam stability arising from surface tension considerations.

It is possible to determine the restoring forces associated with the Gibbs' elasticity mechanism using surface tension versus concentration data.⁽¹⁹⁾ If a given quantity of the bulk material is stretched into the form of a film of thickness, d , the bulk concentration will be reduced by the amount $2\Gamma'/d$, where Γ' is the surface excess in the stretched condition. The conservation of mass requirement, together with the Gibbs' equation, allows us to calculate the increase in surface tension as a function of film thickness. This calculation has been made for $\text{CaO/SiO}_2 = 0.64$ with 0.1 and 0.4 mole percent Cr_2O_3 in solution.

The results of this calculation are shown in Figure 8. For the 0.4 percent composition, there was no appreciable increase in surface tension, even with a nearly infinite amount of thinning. For the 0.1 percent

composition, a small rise was found, but at a film thickness of about 10^{-6} cm, which was probably the lower limit of film thicknesses reached in the foaming studies (based on the failure to observe interference colors). Thus it appears that the contribution of the Gibbs' effect to foam stability was very small, since the restoring forces were not appreciable in the important range of film thicknesses from 10^{-6} to 10^{-2} cm. Only if the effect of Cr_2O_3 on the surface tension had been an order of magnitude greater, would the Gibbs' mechanism be important.

Another surface tension mechanism was introduced by Marangoni,⁽²⁰⁾ which is generally believed to be more important in foaming studies. In contrast to that of Gibbs, the Marangoni mechanism is based on a dynamic model and is not limited to thin films. It relies on the fact that adsorption is a time-dependent process. A freshly formed surface has a "dynamic" surface tension that can be much higher than at equilibrium. The situation in a stretched film is similar to that in a surface that has not been completely aged. There is a temporary increase in surface tension immediately after stretching that acts as a restoring force before the adsorption process can reach equilibrium.

Although it is more difficult to consider the importance of this effect quantitatively, several observations can be cited from the experimental measurements which lend support to the Marangoni mechanism. By varying the bubble rate during the surface tension measurements, it was found that the equilibrium surface tension was obtained when bubbles were formed at intervals of twenty seconds or more. When bubbles were blown every few seconds, however, there was a small increase in surface tension.

This information establishes an approximate value of a few seconds as the time necessary for complete aging.

The same conclusion can be drawn from an approximate diffusion calculation. A "rule of thumb" criterion for the time required for appreciable diffusion to occur is $x = \sqrt{D t}$ or $t = \frac{x^2}{D}$, where t and x are the diffusion time and distance, respectively. Arbitrarily assuming a diffusion coefficient of 10^{-6} cm²/sec for chromium and for a film half-thickness of 10^{-3} cm, $t = (10^{-3})^2 / 10^{-6} = 1$ second. The result indicates that a significant amount of adsorption should occur during a one second aging period. This estimate ties in nicely with the one based on the rates of bubble formation. It is thought that the kinetics of aging is therefore of the right magnitude to render the Marangoni effect operative.

The nature of the foam life-composition curve in Figure 7 lends further support to the Marangoni theory. In very dilute solutions, there is a limitation in that the dynamic surface tension cannot increase greatly over the equilibrium surface tension. (The maximum dynamic tension equals the equilibrium tension at infinite dilution.) In the concentration range near the solubility limit of Cr_2O_3 , there is another limitation, since the bulk phase contains so much solute that it can bring a stretched film to adsorption equilibrium before the elasticity mechanism becomes operative. Thus one would expect there to be an optimum concentration at which this effect is most important, and this optimum concentration was found to be 0.25 mole percent Cr_2O_3 in Figure 7, where a sharp maximum can be seen. There is no apparent way to explain this maximum other than in terms of the Marangoni elasticity mechanism.

Referring again to Figure 7 where data are plotted for $\text{CaO-SiO}_2 = 0.64$, the solubility limit of Cr_2O_3 is about 0.7 mole percent (from Figure 1). Therefore the points for 1.0 and 1.5 mole percent Cr_2O_3 added lie in the two-liquid phase region. As more of the second liquid was introduced, the foam stability was found to increase slightly. Additional experiments were conducted on melts containing 2.5 and 4.0 mole percent Cr_2O_3 , for which the data are not plotted, but are listed in Table II. During these experiments, the foam stability was observed to increase progressively during repeated trials. A plausible explanation for this behavior is that emulsification of the second liquid occurs during bubble agitation. At times, the emulsified droplets were allowed to settle to a separate layer during thirty minute settling periods, and the foam stability was found to fall to its original level. With subsequent measurements, the foam life again increased as before.

Both the emulsified droplets and the suspended platinum flakes mentioned previously are believed to increase foam stability by settling at the sites where three or more bubbles are in contact (Plateau borders). In this way, they retard the coalescence of bubbles and the drainage of liquid from the film lamellae by increasing the effective viscosity of the melt. Since long lasting foams were produced by introducing a dispersed second phase, the effect is an important one that merits further study.

From the results of this investigation, it is believed that Cr_2O_3 can act as a foam stabilizer when it is present in a heterogeneous mixture of phases as well as when it is in solution. For this reason, the Cr_2O_3 level in a steelmaking slag is an important consideration in avoiding foaming problems.

A final word should be mentioned about V_2O_5 as a foaming agent. Until the present, it had been suspected, but not established experimentally, that V_2O_5 induces foaming. In a single experiment (FM-20 in Table II), it was found that V_2O_5 is very potent in this respect.

SUMMARY

The degree of lowering of surface tension by Cr_2O_3 was found to be moderate in comparison with other surface active agents, meaning that the Marangoni elasticity effect is a possible contributor to foam stability. The Gibbs' mechanism must be ruled out, however, because of insufficient surface tension lowering in the dilute solution range. Further support for the Marangoni elasticity mechanism was obtained on the basis of a maximum in foam life with Cr_2O_3 concentration and information on the aging kinetics of the surface.

The viscous nature of silicate melts contributes to foam stability by retarding the drainage of liquid from films, but the extremely high temperature coefficients of foam stability cannot be explained in terms of viscosity, nor can it explain why many viscous liquids are only prone to foaming after a suitable surface active agent has been added.

In addition to its importance in dilute solution, Cr_2O_3 was found to stabilize foams when present in a dispersed second phase.

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REFERENCES

1. A. Decker, Metal Progress, Jan. 1959, 65.
2. J. H. Swisher and C. L. McCabe, Technical Note submitted for publication, Trans. AIME.
3. P. Kozakevitch, Rev. Met. 46, 505 (1949).
4. C. F. Cooper and J. A. Kitchener, J. Iron and Steel Institute 193, 52 (1959).
5. E. Schroedinger, Annalen der Physik 46, 413 (1915).
6. L. R. Barret and A. G. Thomas, J. Soc. Glass Tech. 43, 179t (1959).
7. R. E. Boni and G. Derge, Trans. AIME 206, 53 (1956).
8. J. H. Swisher, Ph.D. Thesis, Carnegie Institute of Technology (1962).
9. S. I. Popel and O. A. Esin, Zhur. Neorg. Khim 2, 632 (1957).
10. T. B. King, J. Soc. Glass Tech. 35, 241 (1951).
11. C. H. Fiske, J. Biological Chem. 35, 411 (1918).
12. J. V. Robinson and W. W. Woods, J. Soc. Chem. Ind. 67, 361 (1948).
13. T. B. King, Unpublished data received by private communication.
14. J. J. Bikerman, "Foams, Theory and Industrial Applications", Reinhold Publishing Co., New York (1953).
15. C. F. Cooper and C. L. McCabe, Research Report, Metals Research Laboratory, Carnegie Institute of Technology, Sept. (1959).
16. H. W. Meyer, Private communication.
17. J. O'M. Bockris and D. C. Lowe, Proc. Royal Soc., London, A226 423 (1954).

18. J. H. Swisher and C. L. McCabe, "Foams, Theory and Industrial Applications", Vol. I, Longmans Green Co.,

author
J. H. Swisher (Ph.D. Thesis - Carnegie Inst. of Tech.) and C. L. McCabe [1962] refs.
Double Code.

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19. C. F. Cooper and J. A. Kitchener, Quarterly Reviews Chem. Soc. 13, No. 1, 71 (1959).
20. C. Marangoni, Nuovo Cimento (2), 5-6, 239 (1871)

Table I. SURFACE TENSION RESULTS

Experiment No.	CaO/SiO ₂ (molar)	mole % Cr ₂ O ₃ added	Surface Tension (dynes/cm)
CR-1	0.64	0.00	389.8
3	"	0.50	376.6
4	"	0.96	375.8
5	"	0.50	373.5
6	"	4.00	345.7
7	"	2.00	350.3
8	"	1.00	374.9
9	"	1.50	367.0
12	"	3.00	347.5
15,16,17	"	0.00	390.0,387.3,388.6
18,19,20	"	"	391.1,388.6,393.3
21,22	"	0.31	381.9,386.1
CR-23,24	0.57	0.00	380.8,379.0
25,26	"	0.24	370.9,371.9
27,28	"	0.48	371.2,375.1
29,30	"	0.73	373.2,370.9
31,32	"	0.97	366.2,364.2
33	"	1.47	347.7
34	"	1.97	346.1
CR-40,41	0.77	0.00	408.4,407.6
44,45	"	0.52	398.1,396.9
46,47	"	1.02	384.0,391.0
48,49	"	1.28	381.0,386.1
50,51	"	1.50	379.9,380.9
52	"	2.00	380.7
53	"	3.00	368.8
54,55	"	4.00	381.0,380.5

Table II. FOAM STABILITY RESULTS

Experiment No.	CaO/SiO ₂ (molar)	Mole % Cr ₂ O ₃ added	Temp. (°C)	Foam Life (sec.)
FM-3	0.64	0.5	1600	34.0
FM-4	0.64	0.25	1585	74.6
			1610	49.4
			1638	37.6
FM-5	0.64	0.75	1600	17.5
FM-6	0.64	1.0	1600	11.9
FM-7	0.64	1.5	1600	19.3
FM-8	0.64	1.5	1600	15.2
FM-10	0.57	0.25	1586	92.3
			1605	71.5
			1632	54.6
FM-11	1.0	0.25	1620	0
FM-13	0.77	0.25	1608	43.3
			1631	30.7
FM-15	0.64	0.1	1600	39.4
FM-16	0.64	2.5	1600	Increased with time
FM-17	0.64	4.0	1600	"
FM-19	1.27	0.24	1600	0
FM-20	0.64	0.5% V ₂ O ₅	1600	~ 150.

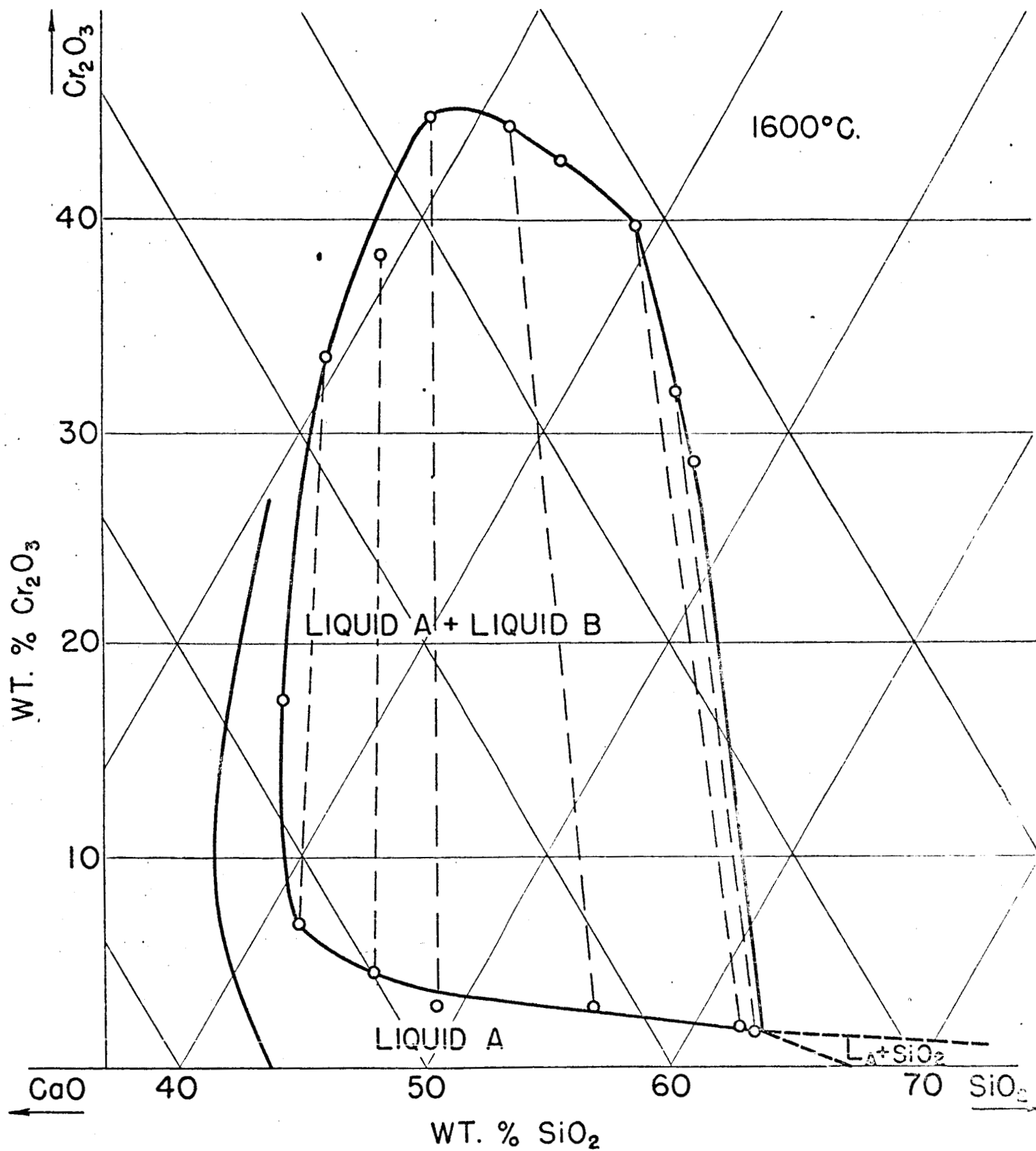


Fig. 1 Miscibility Gap in the CaO-SiO₂-Cr₂O₃ System at 1600°C. (2)

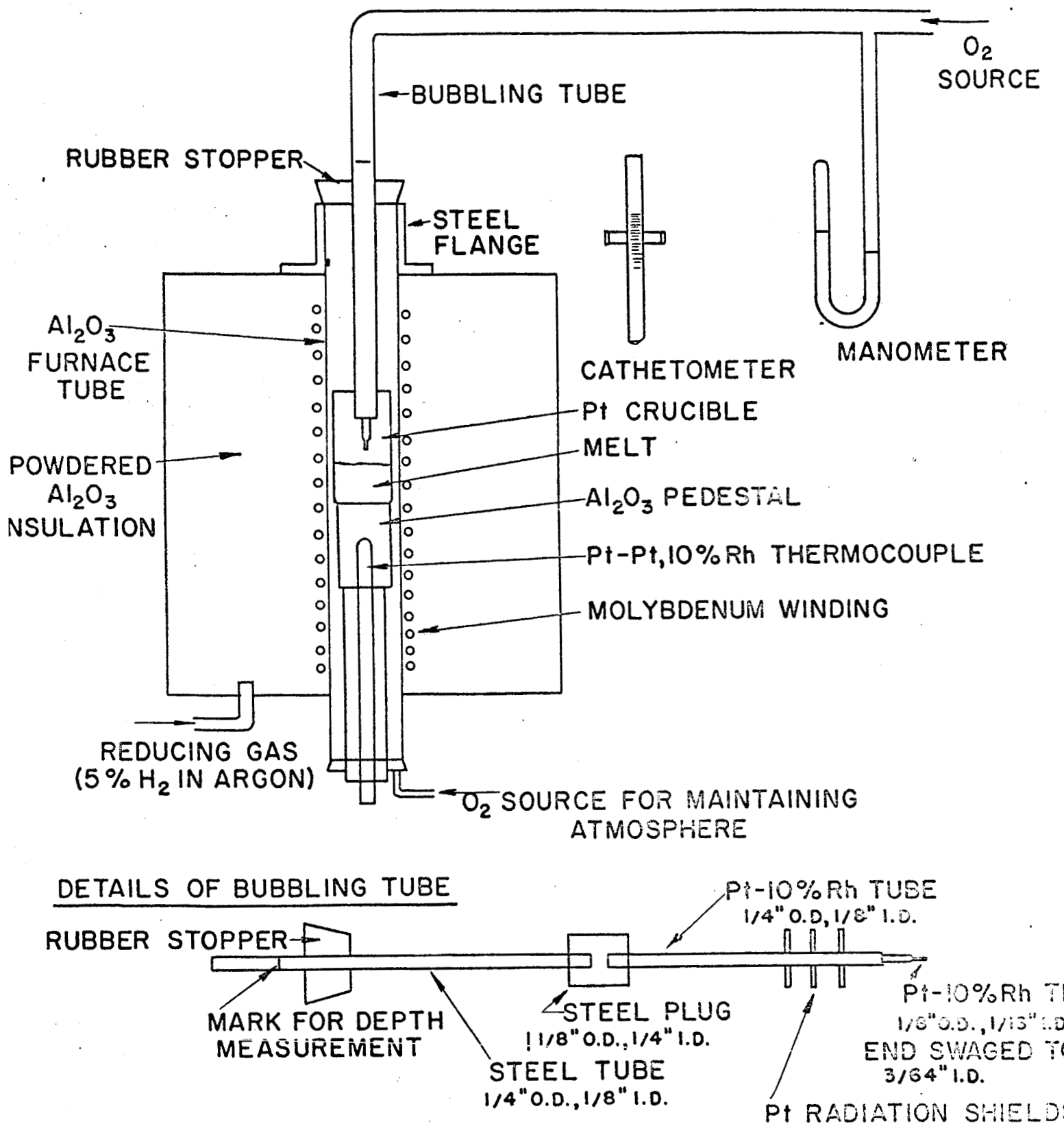


Fig. 2 Apparatus for Surface Tension Measurements.

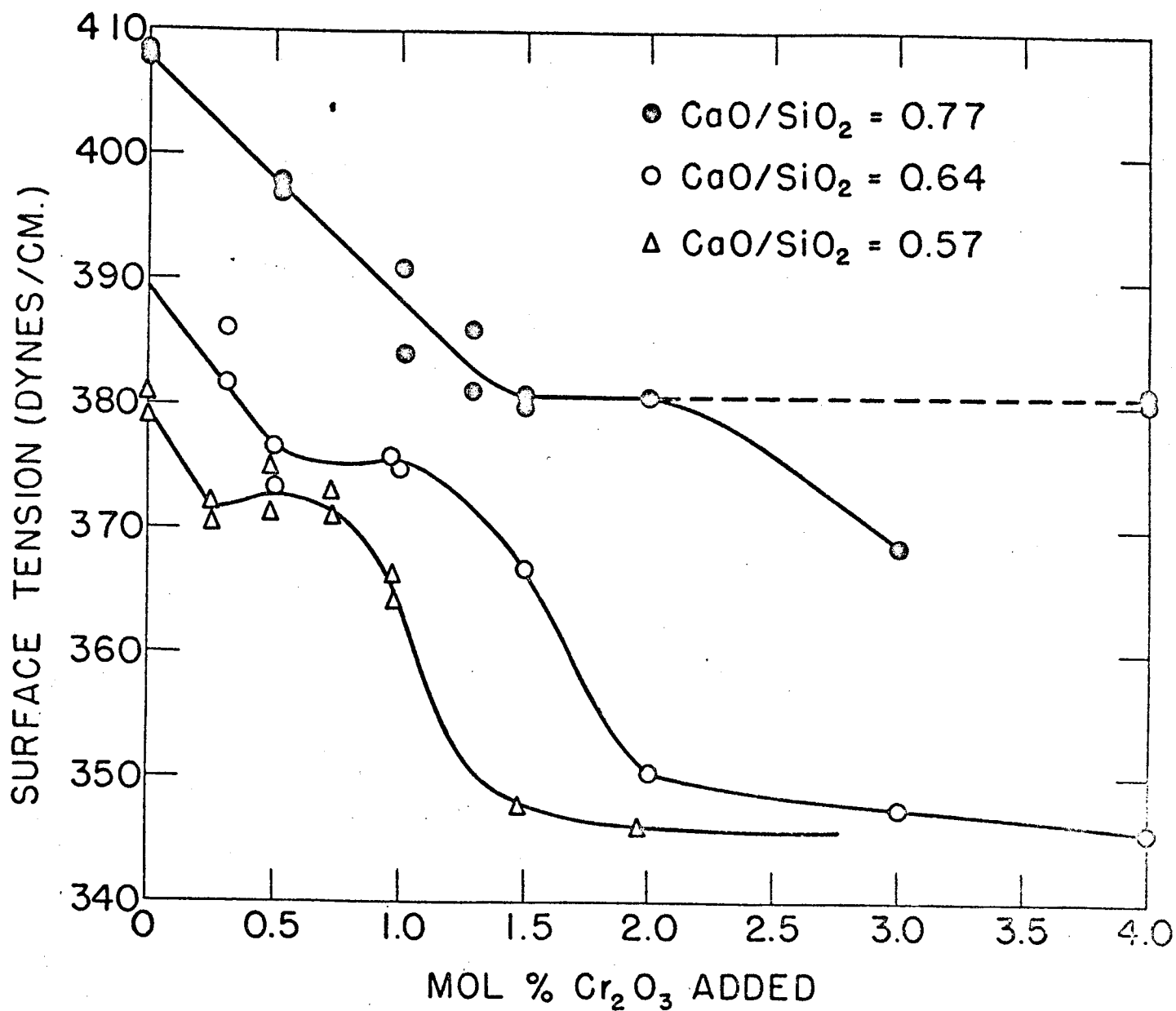


Fig. 3 The Lowering of Surface Tension of CaO-SiO₂ Melts by Cr₂O₃ at 1600°C.

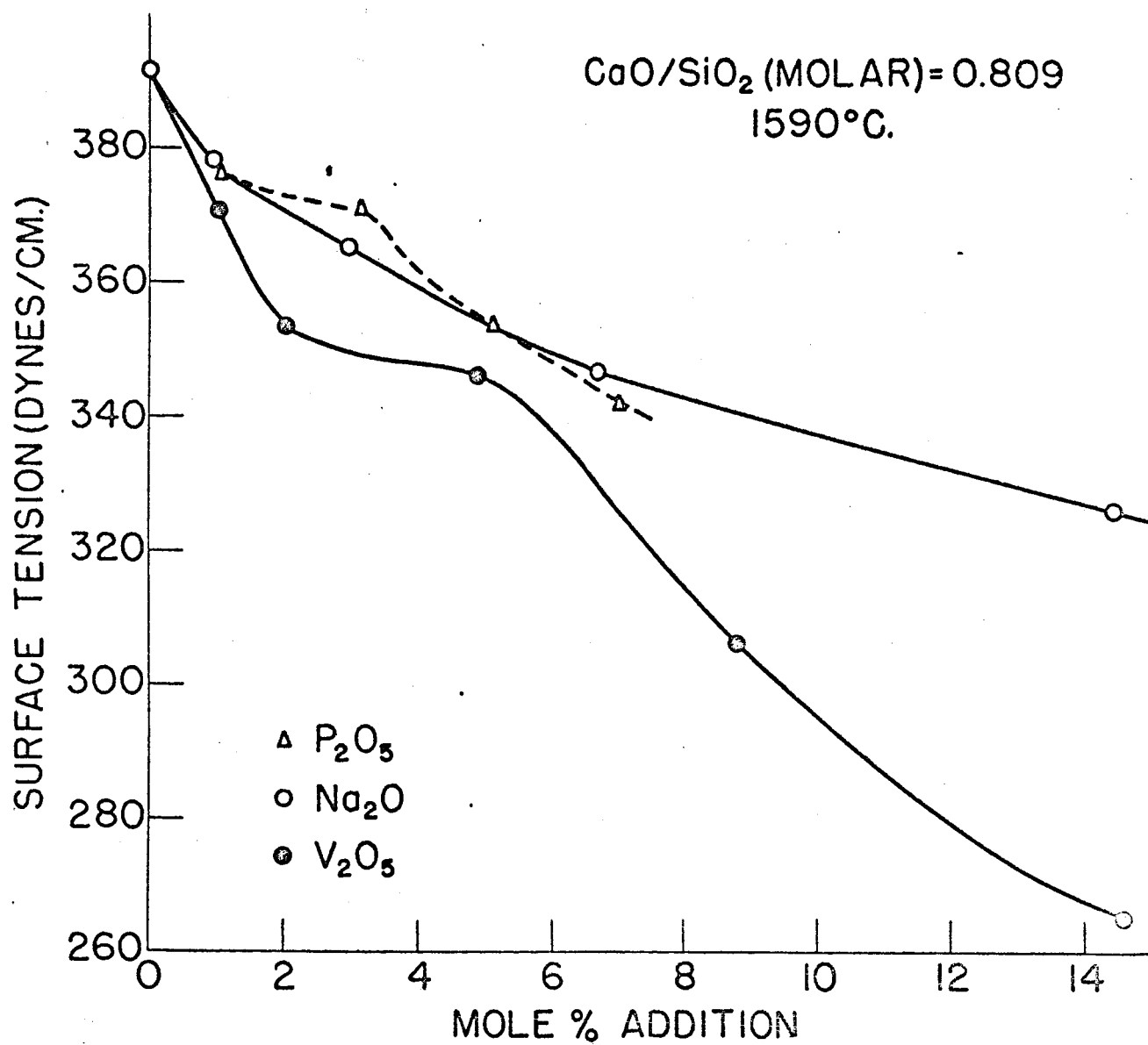


Fig. 4 Similar Surface Tension Data in Other Silicate Systems.⁽¹²⁾

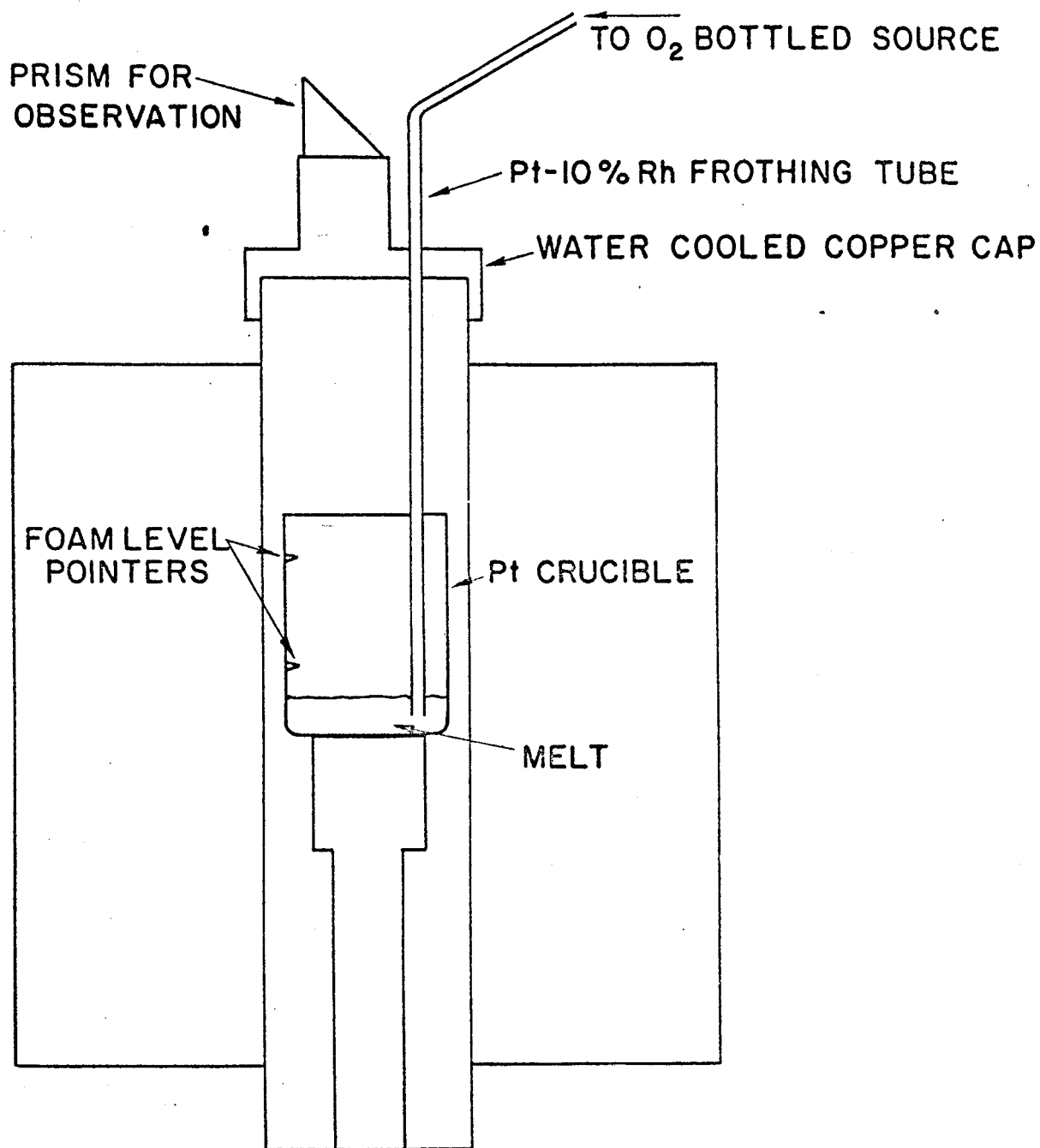


Fig. 5 Experimental Technique for Foam Stability Measurements.

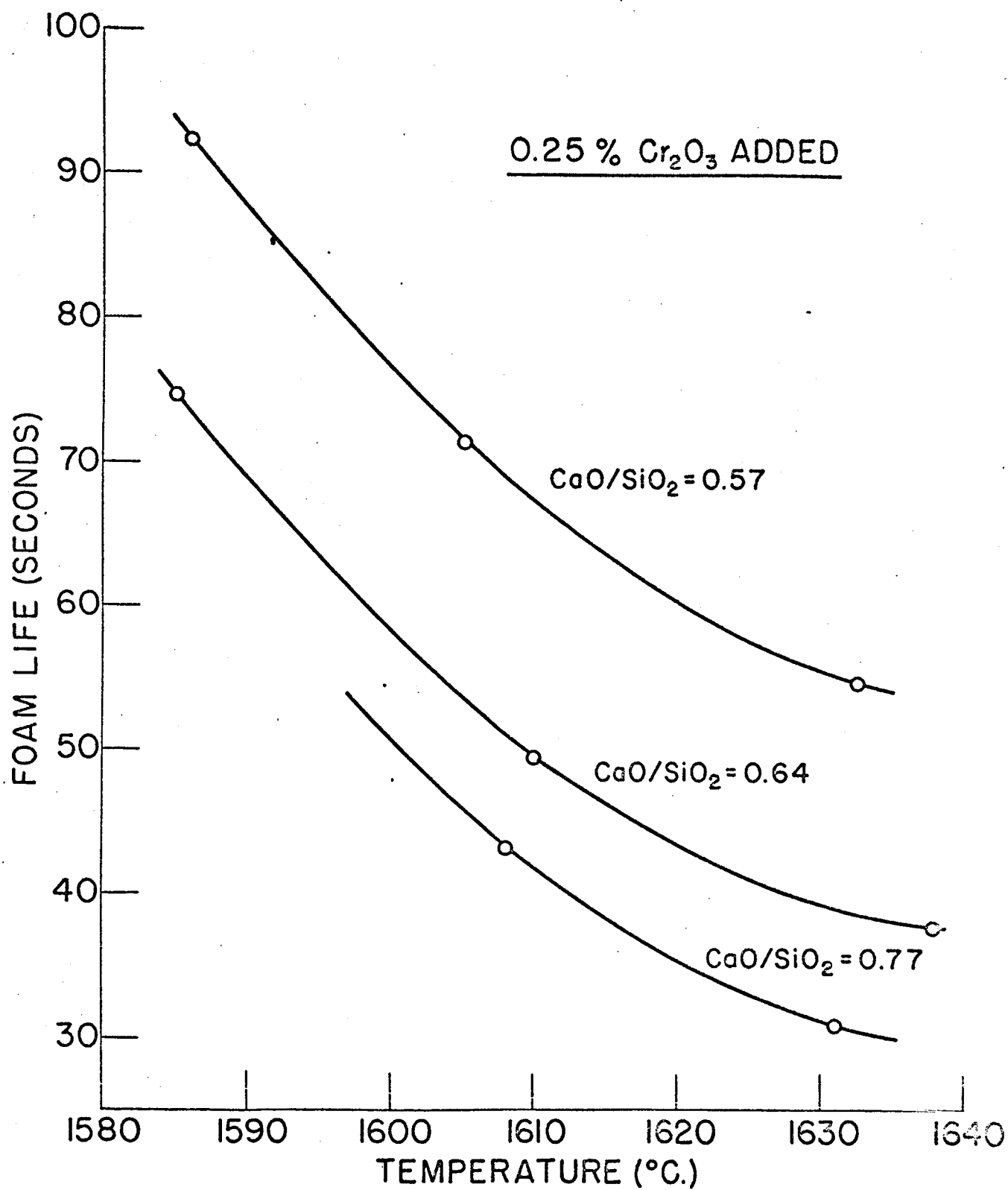


Fig. 6 The Effects of Slag Basicity and Temperature on Foam Stability.

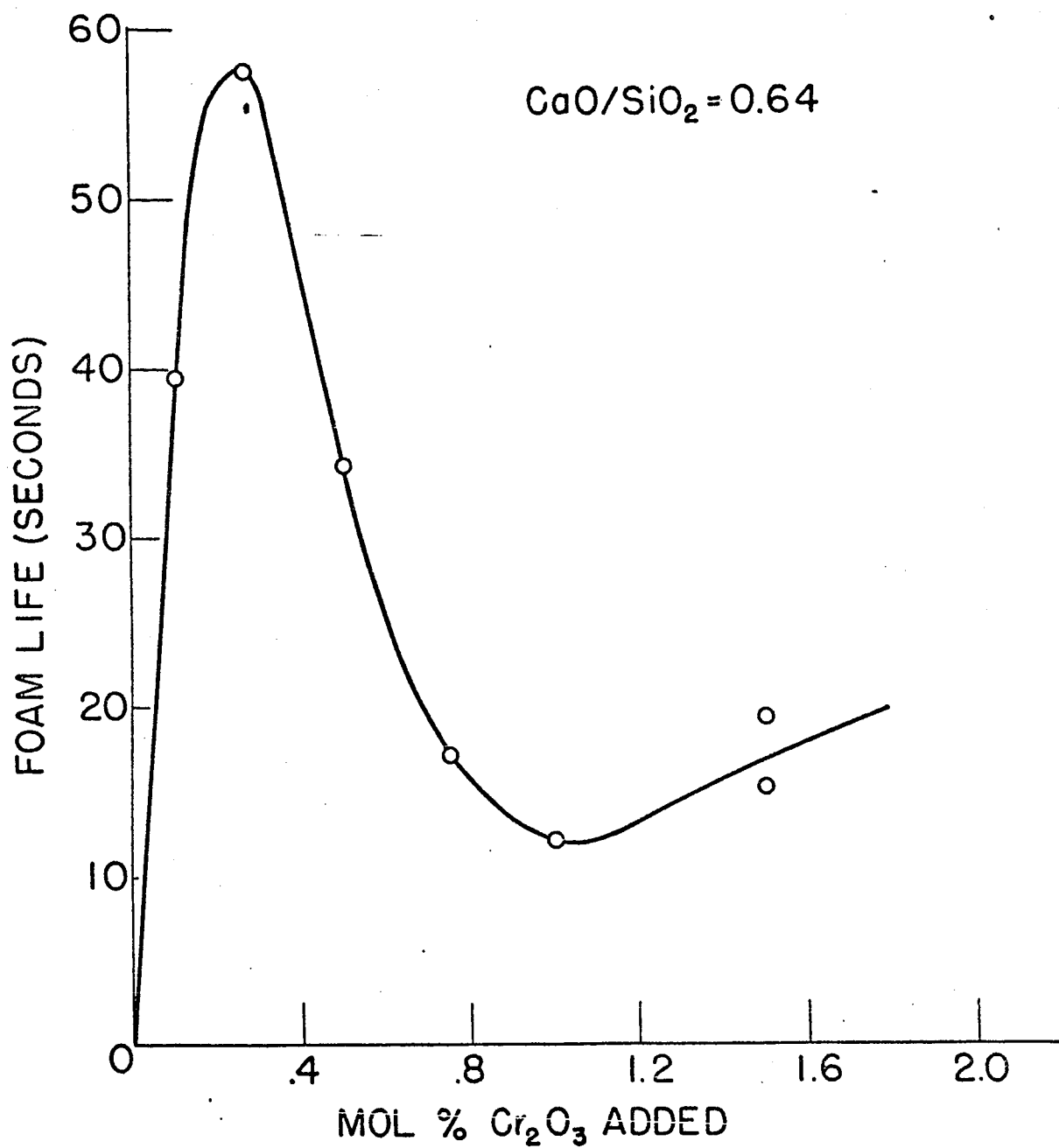


Fig. 7 The Variation of Foam Stability with Cr₂O₃ Concentration.

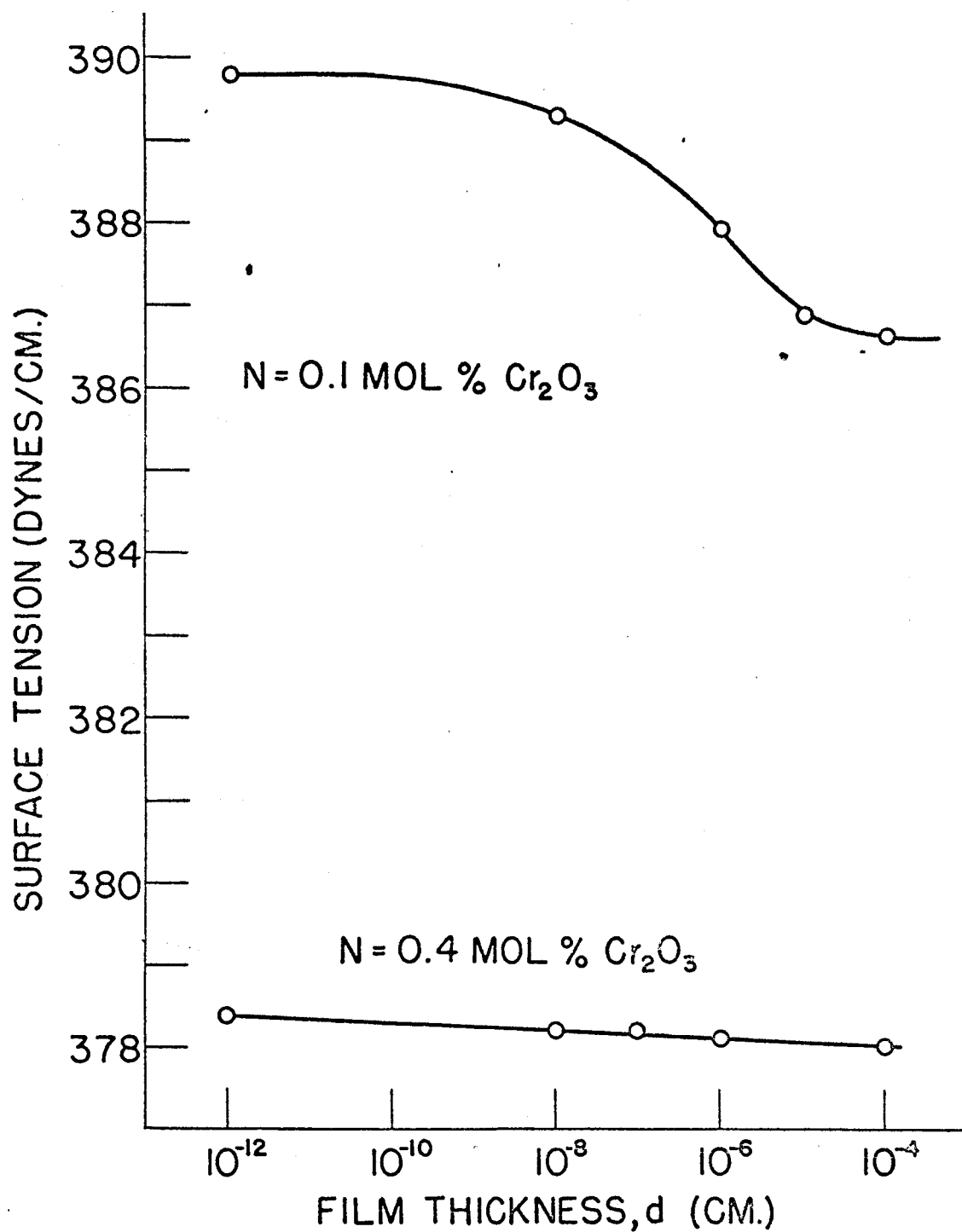


Fig. 8 Magnitude of the Gibbs Elasticity Effect.